9.3 Sensitivity of Tropical Cyclone Track, Intensity, and Orographic Precipitation to Cumulus and Microphysical Parameterization

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1. Introduction

The modeling of tropical cyclones has improved significantly over the past two decades. However, the improvements have largely been made in the area of track prediction. Skill in forecasting intensity is quite low, and accurate quantitative precipitation forecasts are still a difficult challenge. The success/failure of a model forecast can hinge upon the choice of parameterizations of physical processes within the model. In this study the MM5 is used to investigate the sensitivity of tropical cyclone strength, track, and orographic rainfall to various cumulus and microphysical parameterizations available with the MM5. The experiments are performed for one case, Typhoon Bilis (2000), which caused heavy rainfall and damage on Taiwan. A previous study, by Lin et al (2001), used Rutledge and Hobbs microphysical parameterization in simulations of Bilis using the US Navy COAMPS model. Modeled rainfall in that study was much greater than what was observed, and thus brought our interest to pursue a further study. Using the MM5, we hope to improve upon that previous study via an investigation of a suite of different cumulus and microphysical parameterizations.

2. Numerical Simulations of Typhoons Bilis

2.1 Synopsis of the typhoon

Typhoon Bilis (2000) followed an almost straight track approaching Taiwan and was a very intense Category 5 typhoon with a minimum pressure of 915 mb as it made landfall on the southeast coast of Taiwan near Tai-Tung (121.4°E, 23.1°N) around 8/22/14UTC 2000. It produced a maximum wind of 75 ms^{-1} and heavy rainfall of 949 mm in 20 h measured in northeast Taiwan. Just before landfall, Bilis turned north and followed a continuous, cyclonic track across the island, which is similar to many previous observed and simulated TCs passing over Taiwan. A well-defined eye was noted with Bilis as it approached Taiwan.

The observed synoptic environment across East Asia and the northwestern Pacific Ocean at 8/22/00UTC (22/00Z) consisted of Tropical Storm Kaemi following along the central coast of Vietnam before making landfall and dissipating inland of Indo-China Peninsula, and persistent but spatially small areas of high pressure north and northeast of Bilis that moved generally westward through the region of the outer coarse model domain into the middle domain by the end of the simulation period. These high-pressure systems, along with Tropical Storm Kaemi and the north Pacific high, tended to help advect or steer Bilis northwestward toward Taiwan. In addition, a low-level jet (LLJ) existed at 700 mb, which was associated with Bilis' outer circulation and impinged on Taiwan's east coast. This type of LLJ had significant impacts on the formation of heavy orographic rainfall over eastern Taiwan and Kyushu Sanchi when a TC impinges on a mesoscale mountain (Lin et al. 2001). Associated with this LLJ was a moist tongue extending from the low center of Bilis to southeastern Taiwan.

2.2 Model configuration and description of experiments

The model used in this study is the Penn State/NCAR MM5.v3 model. The model solves the fully compressible, nonhydrostatic governing equations in the $\sigma - z$ coordinates. Details of the model can be found in Grell et al. (1994). There are two nested domains designed for the simulations. Domain 1 uses a 21-km grid resolution and 200x200 grid points in the horizontal. Domain 2 uses a 7-km grid resolution and 199x199 grid points, and is one-way nested. The time steps for Domains 1 and 2 are 30 and 10 s, respectively. The Blackadar scheme is used to parameterize the planetary boundary layer (PBL) processes. The 1-km resolution terrain used in this study provides a much higher terrain resolution than that used in most previous studies. Four km resolution land-use data has been used in this study.

The cumulus parameterization sensitivity tests are conducted using four different subgrid scale moist convective parameterizations for different 21-km resolution simulations. These are the Betts-Miller-Janic (BM), Grell, Anthes-Kuo (AK), and the improved Kain-Fritsch (KF) schemes. An additional run is made with no cumulus parameterization. The microphysics parameterization used is the Goddard scheme (Tao and Simpson 1993). A bogus vortex of $V_{\max} = 70\, ms^{-1}$ and $R_{\max} = 75\, km$ was implemented for Bilis simulation initially.

The microphysics sensitivity tests were made using four different microphysical parameterizations. In addition to the Goddard scheme, the simple ice (Duhdia 1989), mixed phase (Reisner 1993), and graupel (Reisner 1998) schemes are used. Four runs were made using a 21 km resolution, using the BM cumulus parameterization throughout. The 21 km results were then taken down to 7 km resolution, and the model was rerun at that resolution in the absence of cumulus parameterization. Two additional sets of sensitivity simulations, i.e. with PBL or latent heat deactivated, were performed to isolate individual effects.

3. The Numerical Results

3.1 Sensitivity of cumulus parameterization

There was a fairly wide range of results using the different cumulus parameterization schemes. The model run with a track and timing closest to observations used the BM scheme (Fig.. 1, dots). Initially, the model cyclone tracks south of the observed system, during the approximately 10 h spin-up period at the start of the model integration. After 10 hours, the track becomes very close to the observed track, being virtually identical to observations as the storm

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crosses Taiwan. After crossing Taiwan, the BM cyclone edges further south than the observed track, and the speed is slightly slower. Prior to landfall in Taiwan around hour 27, the strength of the system was the second strongest of the simulations, though still weaker than observations (Fig.. 2). After landfall, the storm was stronger than observations, and in the middle of all the model runs. However, the modeled cyclones that were stronger later in the model integration were also slower than the BM cyclone, allowing more time for strengthening prior to interaction with Taiwan. Maximum 48 h rainfall associated with the cyclone was 410 mm, far lower than observations, and lower than the other simulations. Sub-grid domain averaged precipitation (Fig. 3) was the second greatest throughout the model integration, below only the AK scheme. Domain averaged grid-scale precipitation was fairly low (Fig.. 4). Total domain averaged precipitation is at or near the top as compared to the other simulations throughout the model integration (Fig.. 6). The percentage of precipitation (Fig. 5) generated by the convective scheme was near 100% initially, steadily declining to around 72% during passage over Taiwan, and then slowly increasing to just over 80% at the end of model integration 80%.

The next closest scheme with regards to the track was the AK scheme. Initially, the modeled cyclone was south of the observed track (Fig. 1, triangles) . After 18 hours, the cyclone nudged northward and took a track across Taiwan very close to the observed storm. Once in the Taiwan Strait, the modeled storm tracks somewhat north of the actual cyclone. Throughout the model integration, the translation speed of the AK storm was faster than observations. The AK run cyclone was the strongest cyclone, and appears to be the fastest to adjust to the model (Fig. 2). The pressure was steady in the 925-930 mb range before landfall in Taiwan, still ~10 mb weaker than the actual storm. The increased strength may be tied to the high amount of sub-grid scale precipitation, the highest of all the schemes tested. Explicit precipitation (Fig. 3) was almost negligible compared to the convective precipitation, which accounted for over 95% of the total precipitation (Fig. 5). There is a slight but notable increase in explicit precipitation as the modeled cyclone crosses over Taiwan around hour 25 (Fig. 4). Total domain averaged precipitation was high initially (Fig. 6), due to the activity of the cumulus parameterization scheme, but later amounts were similar to that seen with the other schemes. Maximum 48 h rainfall over Taiwan was the highest of all the schemes, with 1150 mm of rainfall.

The Grell scheme produced a cyclone that tracked slightly slower and to the north of the observed track, after an initial jog south that was seen in the other simulations (Fig. 1, squares). The intensity was the weakest of all the modeled cyclones (Fig. 2). The adjustment time for the storm was the longest, and it failed to strengthen to any degree after adjusting. Prior to interaction with Taiwan, the pressure dropped to only as low as 936 mb. The Grell scheme was the least active of all, and the amount of explicit precipitation was exceeded only by the simulation with no subgrid-scale parameterization implemented (EX) (Figs. 3 and 4). The percentage of connective precipitation peaked at 65% at hour 3, and decreased to a range of 30-40 % after hour 8 (Fig. 5). Domain averaged precipitation was comparable to the other schemes (Fig. 6). A total of 657 mm of rain was seen over Taiwan during the 48 hour model integration.

The storm in the KF simulation was the slowest moving of all the 21 km storms. The track (Fig. 1, stars) initially went to the south, then was very similar to the observed track until crossing Taiwan. Thereafter, the modeled storm veered north and failed to make landfall in China. The initial weakening during the adjustment period was the greatest of all (Fig. 2). However, the pressure recovered and reached a low of 939 mb before landfall in Taiwan. The activity of the subgrid-scale scheme was in the middle of the spectrum (Fig. 3). Convective precipitation was about twice as much as in the Grell scheme, and about a third less than in the BM scheme. The amount of grid-scale precipitation was comparable to that with the BM scheme (Fig. 4). The percentage of convective precipitation (Fig. 5) was 5-10% less than the BM scheme for most of the model integration. Total domain precipitation was in the same range as seen in the other 21 km simulations (Fig. 6). The maximum 48 h rainfall over Taiwan was 792 mm, second highest.

When turning off the cumulus scheme, the modeled cyclone tracks slightly south of the observed track prior to striking Taiwan (Fig. 1, circles). Afterward, the track was slightly to the north of observations, and slower. The cyclone achieved a strength of 942 mb (Fig. 2). Despite having no contribution from rainfall by a subgrid-scale scheme, domain averaged precipitation was similar to the other simulations after the initial adjustment period (Fig. 6). Maximum 48 h rainfall over Taiwan was 673 mm.

3.2 Sensitivity to microphysical parameterization

The results using the four different microphysical parameterizations were remarkably similar to one another. Here we examine the results of the 7 km resolution simulations. The tracks of all four simulations are virtually the same, as are the speeds of the simulated cyclones. The simulated cyclone tracks are very close to the observed track, indicating that the choice of microphysics has little effect on track.

The four experiments all attained pressure down to the 935-940 mb range, about 20 mb weaker than observed (Fig. 8). The Reisner2 simulation (RG) was systematically weaker than the other simulations by 3-5 mb. As in the cumulus sensitivity experiments, the cyclone required 8-12 hours to fully adjust to the model environment. Interaction with Taiwan resulted in the weakening of the simulated typhoons by approximately 25 mb. Thereafter, the cyclone strengthened by an average of 12 mb before interaction with Taiwan. Once in the Taiwan Strait, the pressure of the modeled typhoons leveled off. The behavior of the pressure in the observed typhoon was quite different, being stronger than the simulations prior to landfall, and weaker than the simulations after.

The distribution of rainfall was similar in the four cases, though the amounts varied slightly. Greatest rainfall amounts were seen using the Goddard scheme (GD), with a 48 hour total of 820 mm over the CMR. The mixed phase (Mix) and RG simulations were the next highest, with 704 and 703 mm respectively. The lowest 48 h amounts were seen using simple ice (SI), with 633 mm. Observed 48 h rainfall over the CMR of Taiwan near 1200 mm. Similar results were seen with the grid-averaged amounts (Fig. 9). The GD scheme produced the greatest amounts. The mixed phase and RG schemes were around .2 mm/hr below the GD, and the simple ice scheme was slightly below these 2 schemes.

We have performed two sensitivity experiments by deactivating the PBL friction or the latent heating of Typhoon Bilis. The tracks are shown in Fig. 10. It appears that by deactivating PBL (Fig. 10a) or latent heating (Fig. 10b), both cyclones are weaker and deflected further to the north.

4. Conclusions

In this study an evaluation of cumulus and microphysical parameterization is made on for a real case, Typhoon Bilis. The track, strength, and rainfall appear to be extremely sensitive to the choice of cumulus parameterization. More active cumulus parameterizations, i.e. BM and AK, generate precipitation more quickly, allowing the cyclone to deepen more quickly after adjusting to the model. This allows more latent heat release, and may contribute to the faster motions than seen in the simulations using the Grell and KF schemes. The simulation using the least active scheme, Grell, produced the weakest cyclone, while the second least active, KF, had the storm track that deviated most from observations. The choice of microphysical parameterization had only a modest affect on rainfall, with greatest amounts using the Goddard scheme, while little significant difference was seen in strength and track. Similar behaviors with the cumulus and microphysics schemes can be seen in studies by Kuo et al. (1996) and Wang and Seaman (1997) in modeling of mid-latitude systems. Both sensitivity experiments without PBL or latent heating produce weaker cyclones and force the cyclones to deflect further to the north.

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Figure Captions

Fig. 1: Tracks of Typhoon Bilis (2000) pressure centers from the 21 km simulations. Positions are every 6 h, and hours are indicated every 12 hr. Observed track is denoted by outlined TC symbols; BM-dots; Grell-squares; KF-stars; AK-triangles; EX-circles

Fig. 2: Pressure traces of the 21 km simulations. Squares show actual pressure.

Fig. 3: Domain averaged convective (subgrid-scale) precipitation in the 21 km simulations

Fig. 4: Domain averaged explicit (grid-scale) precipitation in the 21 km simulations

Fig. 5: Percentage of total domain averaged precipitation from convective precipitation in the 21 km simulations

Fig. 6: Total domain averaged precipitation in the 21 km simulations

Fig. 7: Tracks of Typhoon Bilis (2000) pressure centers from the 7 km simulations. Positions are every 6 h. Observed track is denoted by outlined TC symbols; Si-squares; Mix-triangles; GD-dots; RG-stars

Fig. 8: Pressure traces of the 7 km simulations. Squares show actual pressure.

Fig. 9: Total domain averaged precipitation in the 7 km simulations

Fig. 10: Tracks of fake Bilis cyclones with (a) PBL and (b) latent heating deactivated.

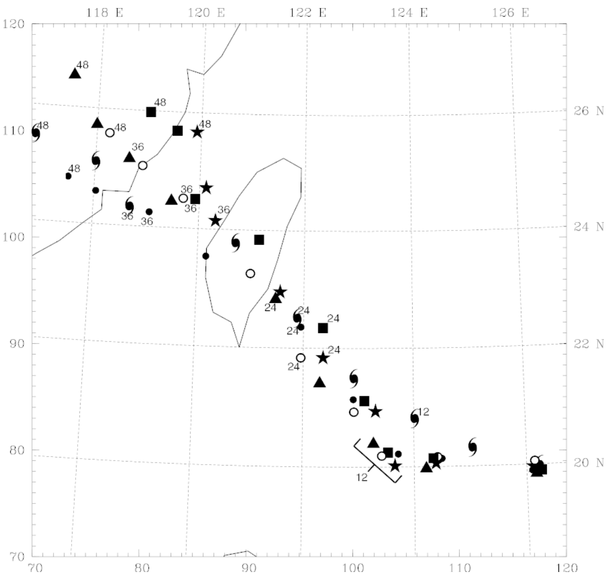
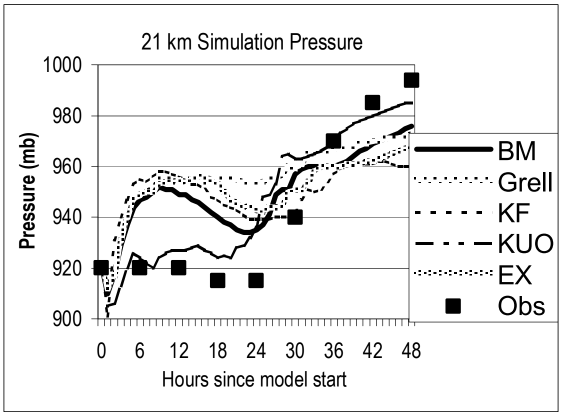


Fig. 1



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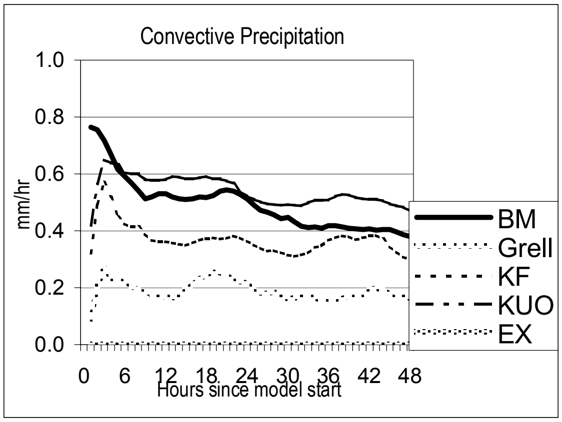

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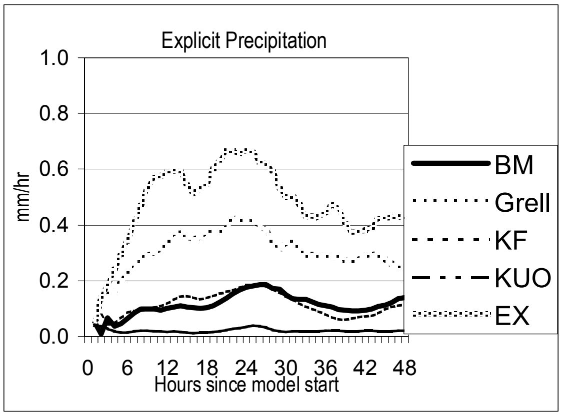

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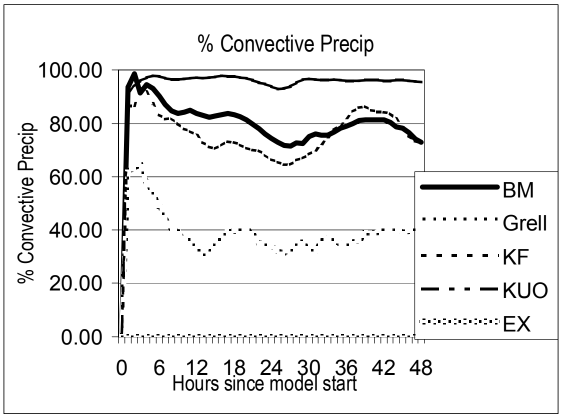
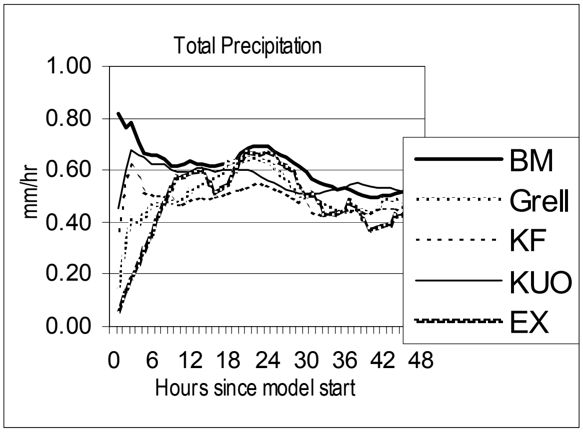
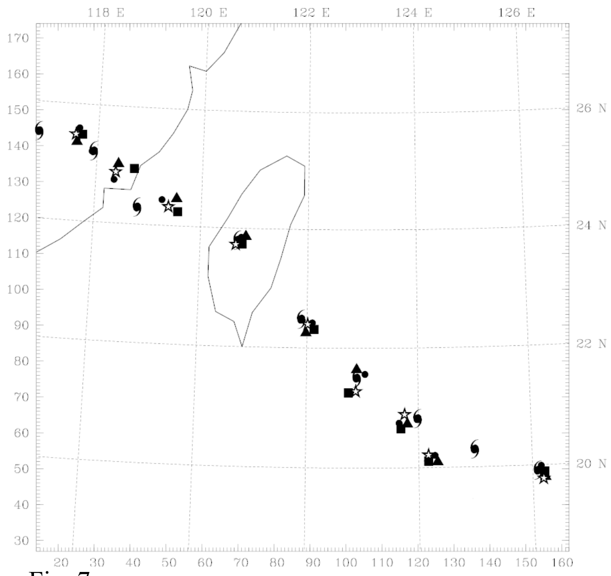


Fig. 5



Fig, 6



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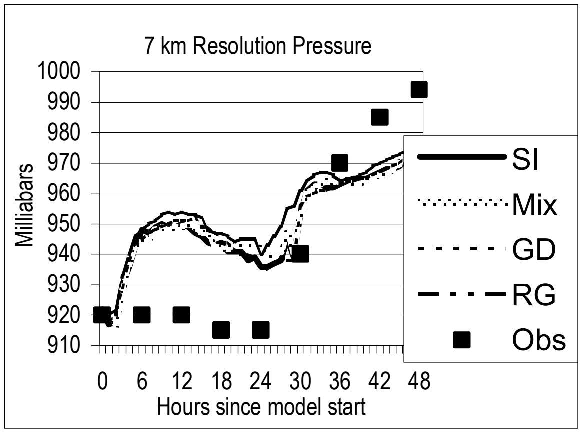

Fig. 8

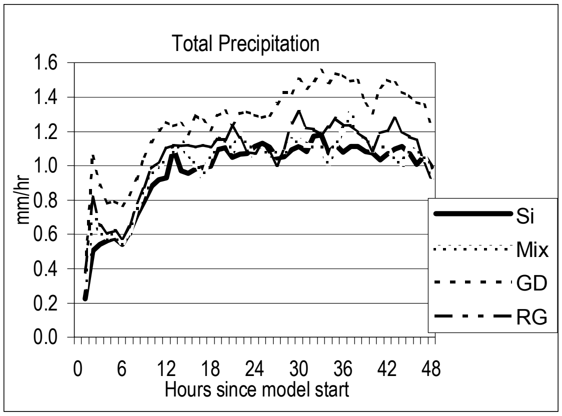

Fig. 9

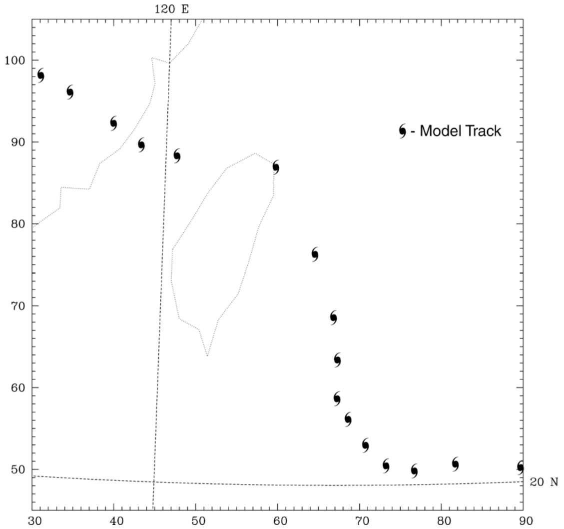

Fig. 9

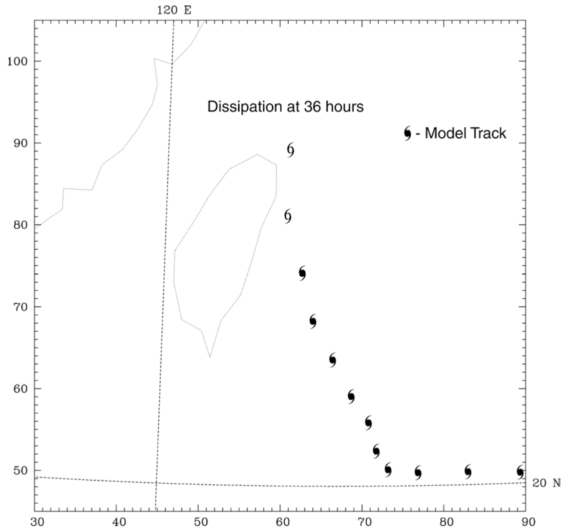

Fig. 10b